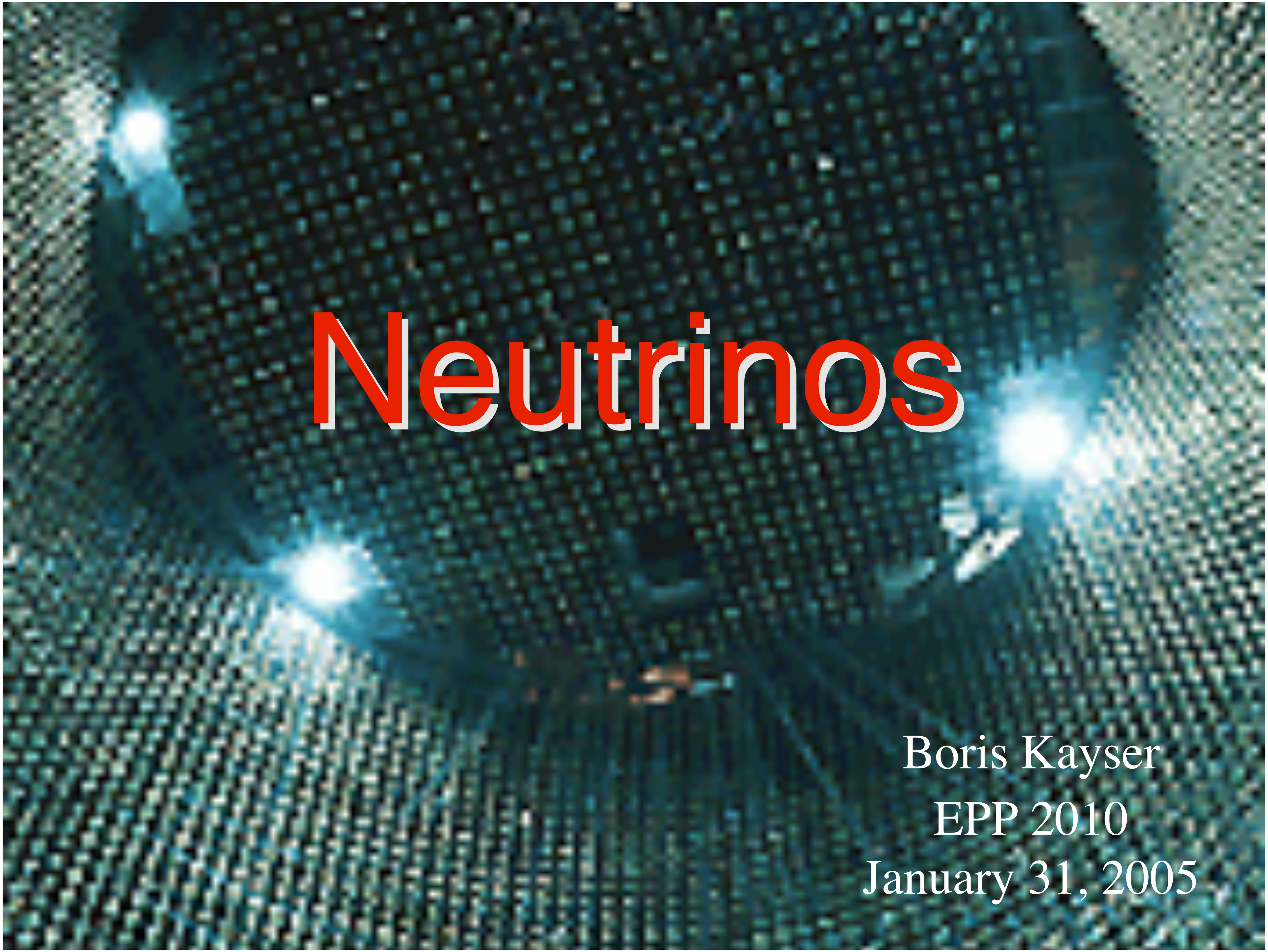


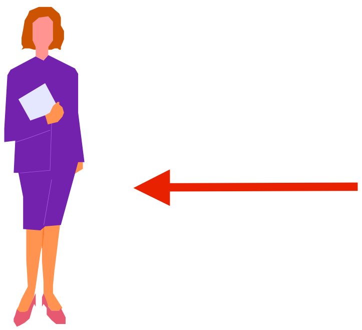
Neutrinos

Boris Kayser

EPP 2010

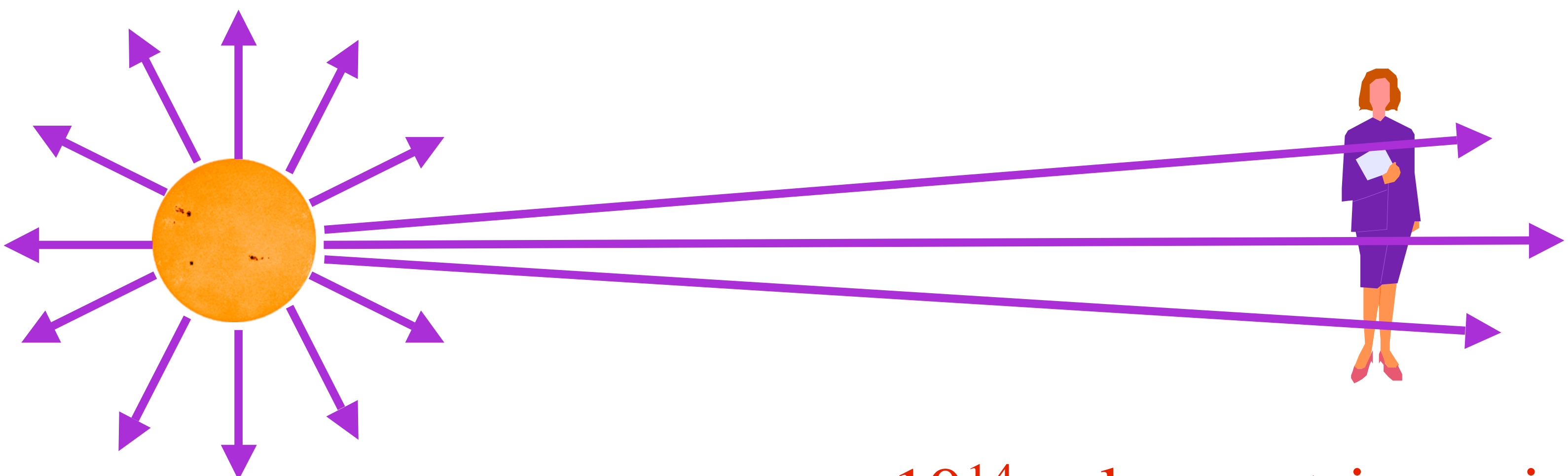
January 31, 2005

Neutrinos Get Under Your Skin



Inside each person:

$> 10^7$ neutrinos from the Big Bang



$\sim 10^{14}$ solar neutrinos zip through every second.

Neutrinos are Abundant

We humans, and all everyday objects, are made of electrons, protons, and neutrons.

But in the universe as a whole —

~ 10^9 neutrinos for each electron, proton, or neutron.

Neutrinos and photons are the most abundant particles in the universe.

If we wish to understand the universe, we must understand neutrinos.

The Growing Excitement of Neutrino Physics

K2K confirms atmospheric oscillations

KamLAND confirms solar oscillations

Nobel Prize for neutrino astroparticle physics!

SNO shows solar oscillation to active flavor

Super K confirms solar deficit and "images" sun

Super K sees evidence of atmos-pheric neutrino oscillations

Nobel Prize for $\overline{\nu}$ discovery!

LSND sees possible indication of oscillation signal

Nobel prize for discovery of distinct flavors!

Kamioka II and IMB see supernova neutrinos

Kamioka II and IMB see atmospheric neutrino anomaly

SAGE and Gallex see the solar deficit

LEP shows 3 active flavors

Kamioka II confirms solar deficit

2 distinct flavors identified

Davis discovers the solar deficit

Reines & Cowan discover (anti)neutrinos

Fermi's theory of weak interactions

Pauli Predicts the Neutrino

1930 1955 1980 2005

What Have We Learned?

The Leptons and their Flavors

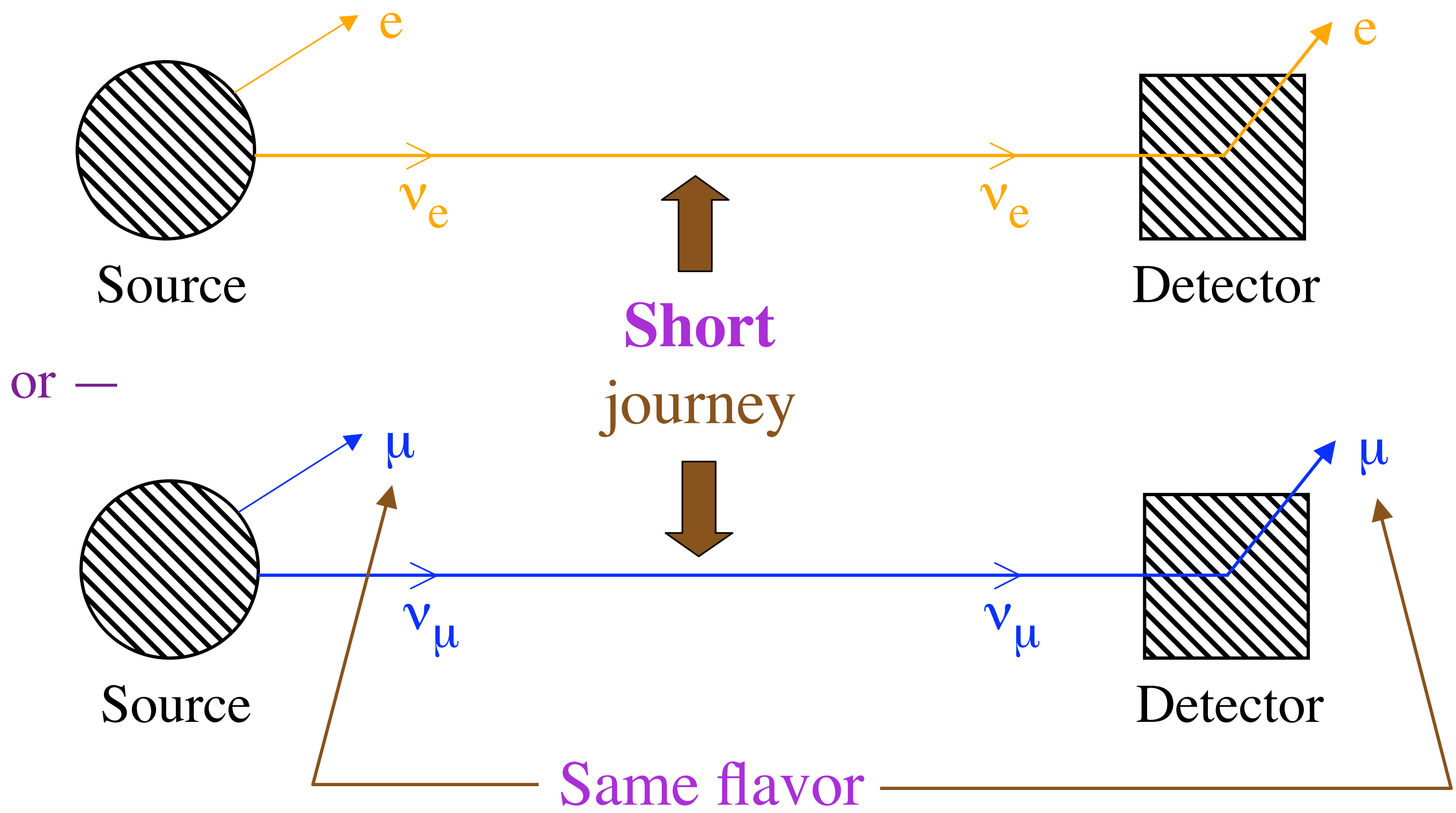
Charged Lepton	Mass	Associated Neutrino
Electron (e)	1	ν_e
Muon (μ)	200	ν_μ
Tau (τ)	3500	ν_τ

What does "associated" mean?

A neutrino is created together with a charged lepton.

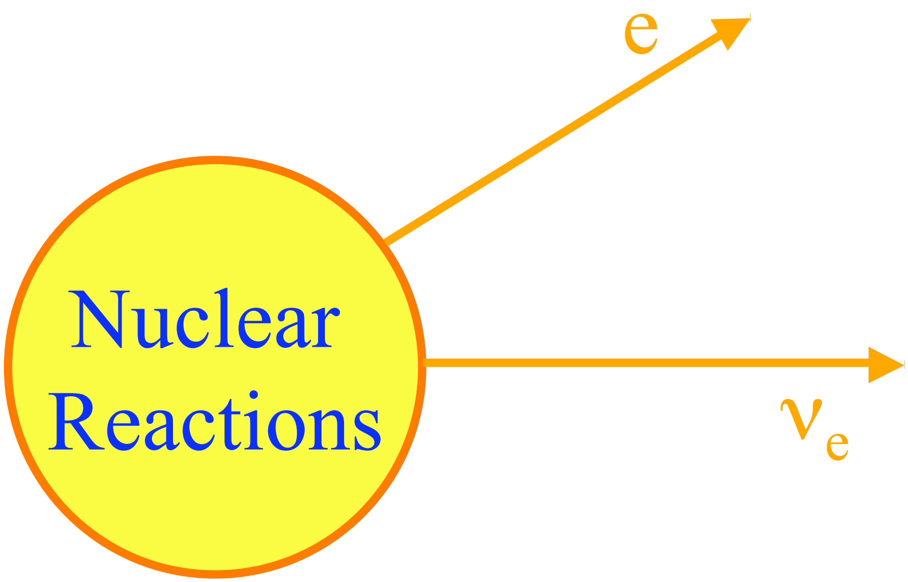
When a neutrino interacts with a detector, it creates a charged lepton.

The neutrino and charged lepton flavors match:



Neutrino Flavor Change

In the core of the sun —



Solar neutrinos are all born as ν_e , not ν_μ or ν_τ .

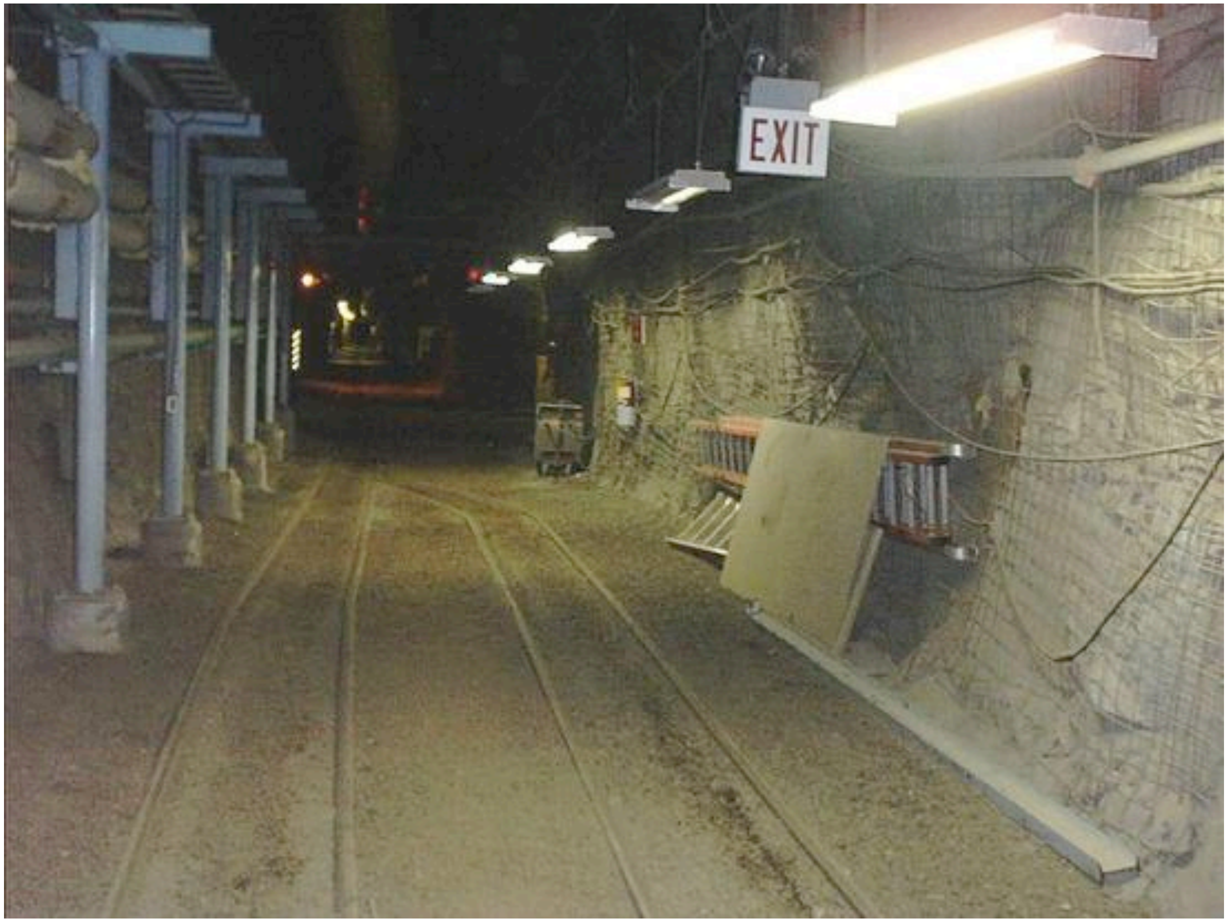


Photo courtesy of SNO

In the Creighton nickel mine, 6800 feet below Sudbury, Canada, is the Sudbury Neutrino Observatory (SNO).

The SNO detector.

The central sphere is 40 feet across, and is filled with heavy water.

Photo courtesy of SNO

SNO detects solar neutrinos in several different ways.

One way counts ———

$$\text{Number }(\nu_e)\ .$$

Another counts ———

$$\text{Number }(\nu_e) + \text{Number }(\nu_\mu) + \text{Number }(\nu_\tau)\ .$$

SNO finds ———

$$\frac{\text{Number }(\nu_e)}{\text{Number }(\nu_e) + \text{Number }(\nu_\mu) + \text{Number }(\nu_\tau)} = 1/3\ .$$

All the solar neutrinos are born as ν_e .

But 2/3 of them morph into ν_μ or ν_τ before they reach earth.

Given time, neutrinos can change flavor.

Once a proton, always a proton (until death).

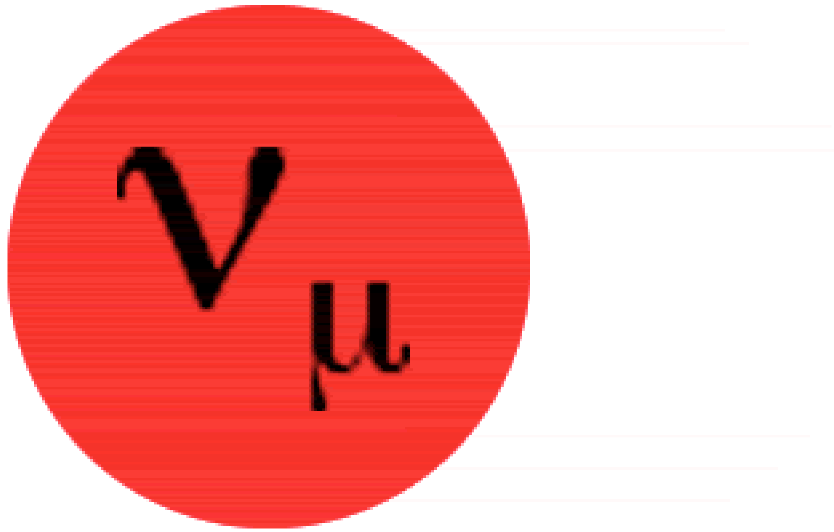
But once a ν_e , **not** always a ν_e .

Evidence For Flavor Change (Since 1998)

Neutrinos	Evidence of Flavor Change
Solar	Compelling
Reactor	Very Strong
Atmospheric	Compelling
Accelerator	Strong

Almost all of these flavor changes are predicted to have an oscillatory character.

Neutrino Oscillation



Neutrino Mass

Neutrinos have long been known to be very much lighter than the other known particles.

Are neutrinos —

— **Massless** bundles of pure energy, like photons?

or

— Particles with **Masses,** like the quarks?

Neutrino flavor change with time

➡ Neutrinos have nonzero **Masses**.

Change of neutrino flavor *with time*

➡ A ν has a sense of time.

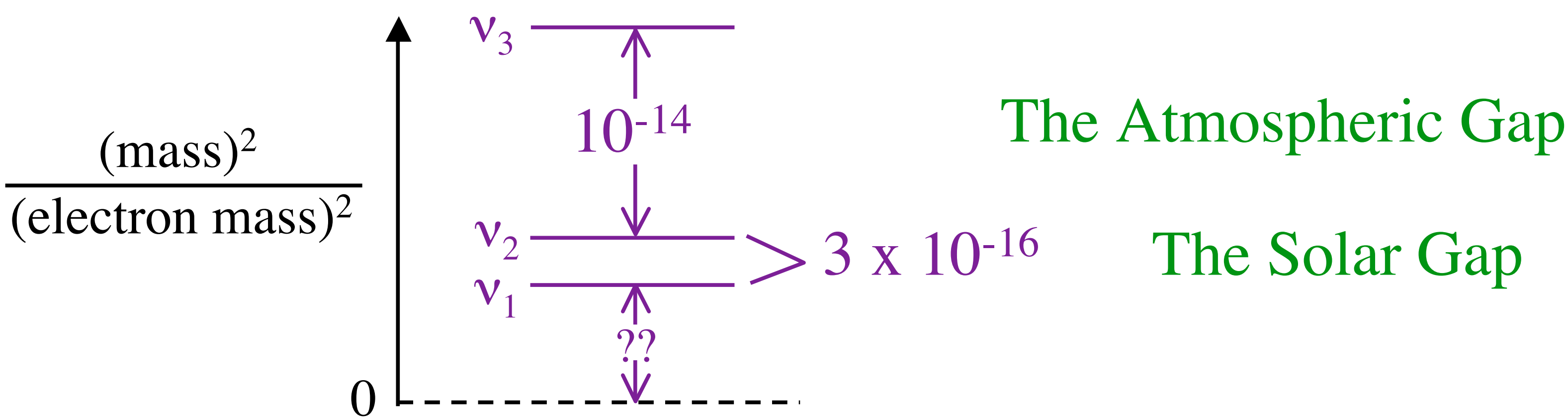
Einstein ➡ Only a particle with mass can have a sense of time.

Therefore, neutrinos have nonzero masses.

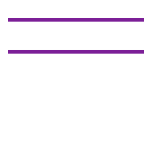
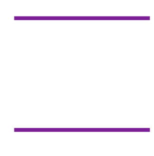
The Neutrino Spectrum

There are at least 3 neutrinos of definite mass.

They are called ν_1, ν_2, and ν_3, and account for all observed flavor changes except the one reported by the Liquid Scintillator Neutrino Detector (LSND).



The spectrum could be

 instead of  .

Neutrino Mixing

A ν_μ can morph into a ν_τ because neither is a particle.

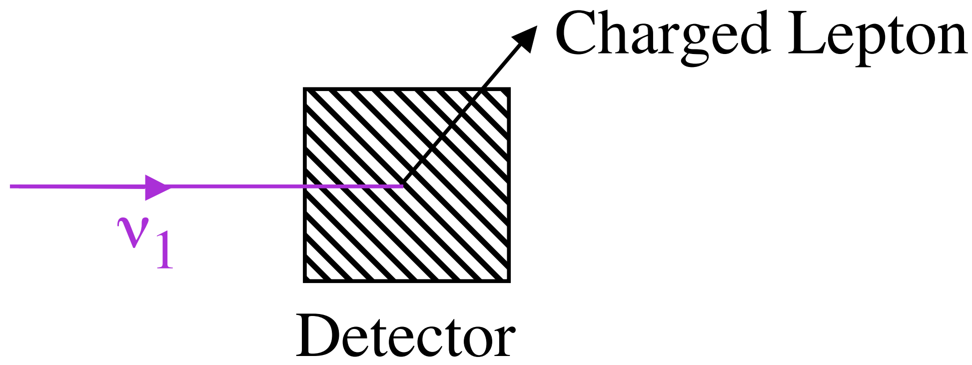
The neutrino particles – the objects with definite masses – are ν_1, ν_2, and ν_3.

ν_e, ν_μ, and ν_τ are different **mixtures** of ν_1, ν_2, and ν_3.

This is called **neutrino mixing**.

During travel, the ν_μ mixture can evolve into the ν_τ mixture.

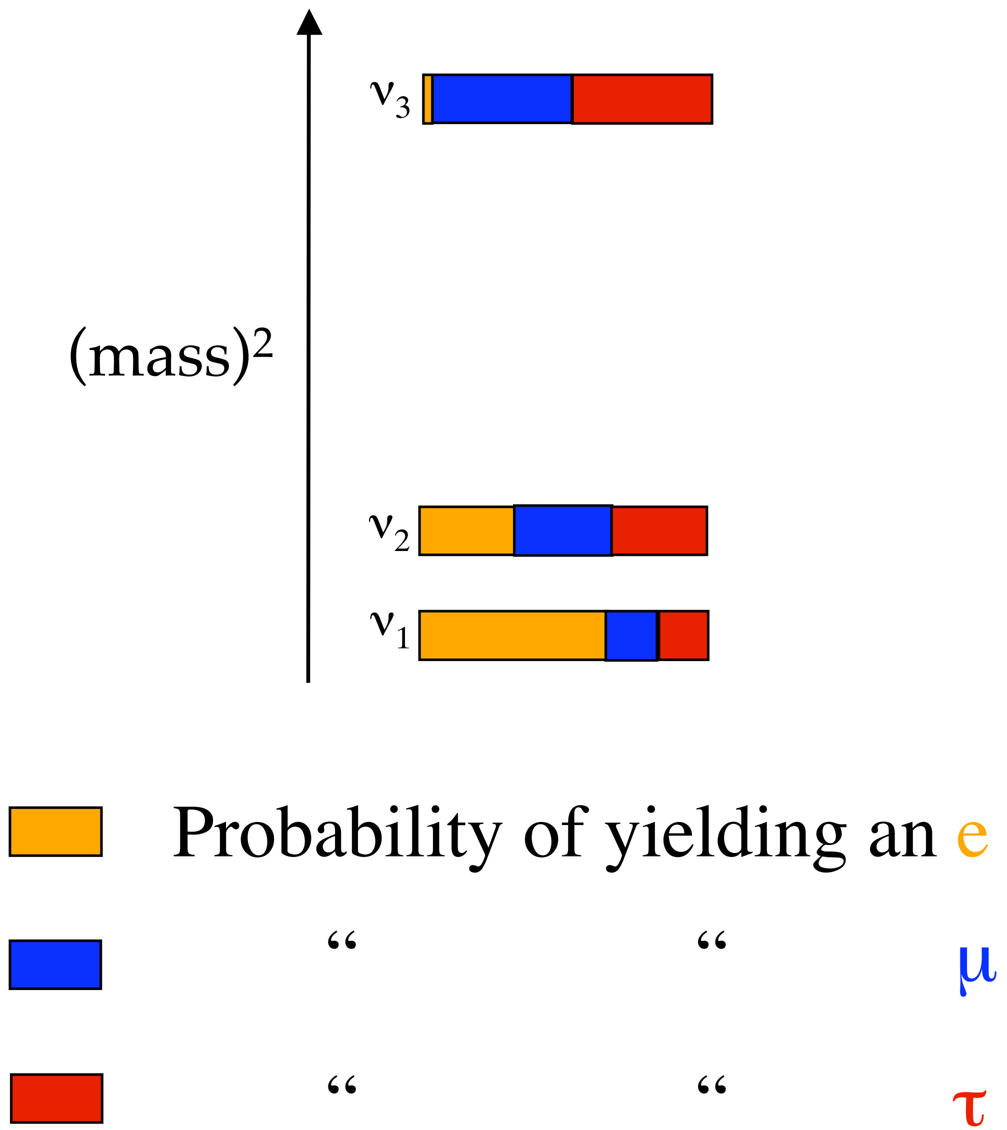
In —



the charged lepton can be an e, μ, or τ.

Similarly for an incoming ν_2 or ν_3.

The Spectrum, Showing the Flavor Probabilities



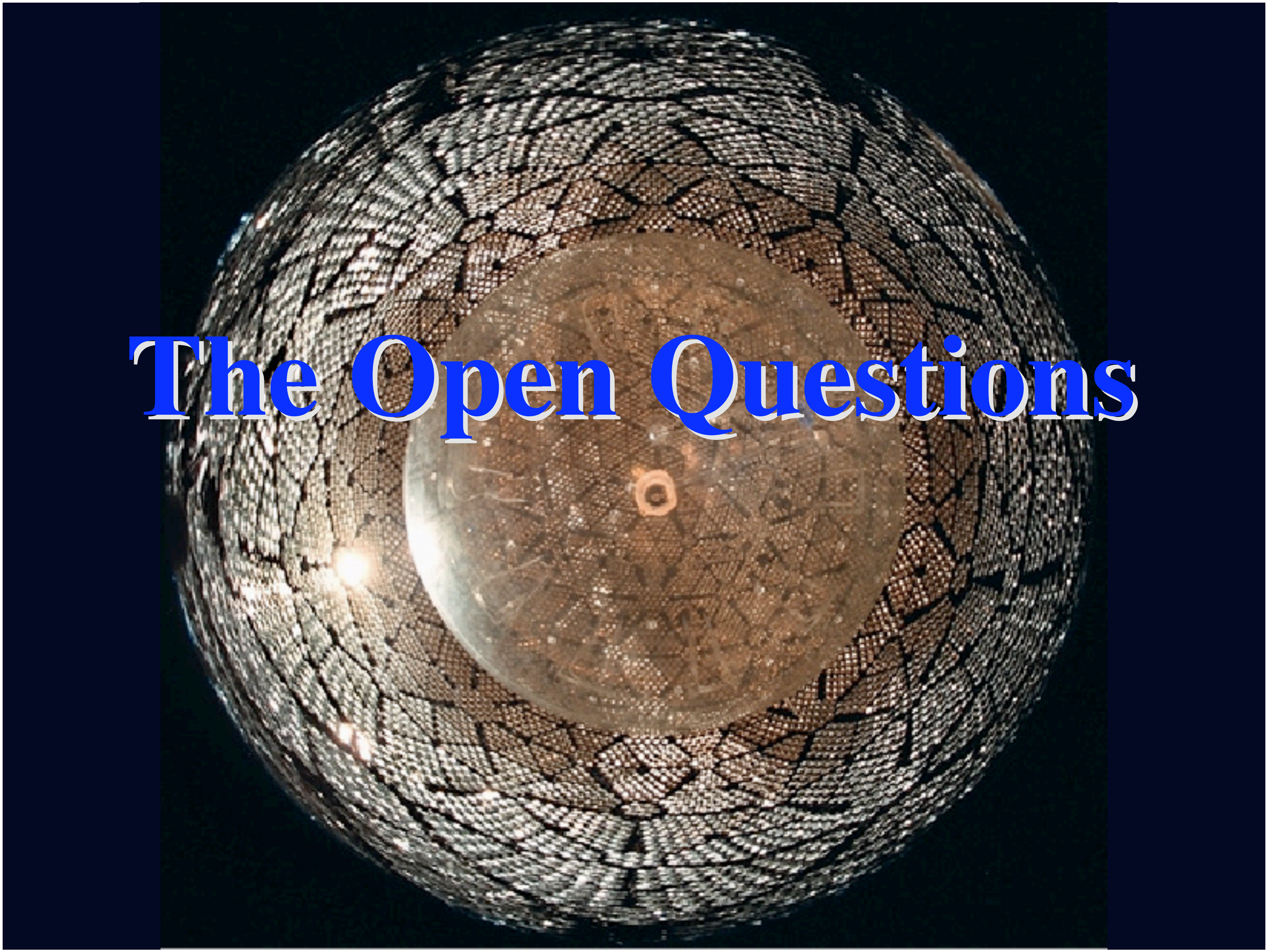
The Liquid Scintillator Neutrino Detector (LSND) Oscillation

					Number
Positive Quarks	u	c	t		**3**
Negative Quarks	d	s	b		**3**
Charged Leptons	e	μ	τ		**3**
Neutrinos	ν_1	ν_2	ν_3	?	**?**

If LSND is confirmed, there are at least **4** neutrinos, ν_1, ν_2, ν_3, and ν_4, breaking the symmetry.

One mixture of these **4** neutrinos, a sterile neutrino, doesn't experience any of the known forces except gravity.

The Open Questions



The discovery of
neutrino mass and mixing

⇓

Open questions about neutrinos and
their connections to other physics

⇓

Need for a coherent strategy
for getting answers

⇓

A year-long study of the future of neutrino physics, sponsored by the American Physical Society Divisions of –

Nuclear Physics

Particles and Fields

Astrophysics

Physics of Beams

The APS Multi-Divisional Neutrino Study

- ➢Over 200 Participants
- ➢Seven Working Groups
- ➢Organizing Committee (Four members from abroad): Janet Conrad, Guido Drexlin, Belen Gavela, Takaaki Kajita, Paul Langacker, Keith Olive, Bob Palmer, Georg Raffelt, Hamish Robertson, Stan Wojcicki, Lincoln Wolfenstein
- ➢Co-Chairpersons: Stuart Freedman, Boris Kayser

Neutrinos and the New Paradigm

- What are the masses of the neutrinos?
- What is the pattern of mixing among the different types of neutrinos?
- Are neutrinos their own antiparticles?
- Do neutrinos violate matter – antimatter symmetry?

Neutrinos and the Unexpected

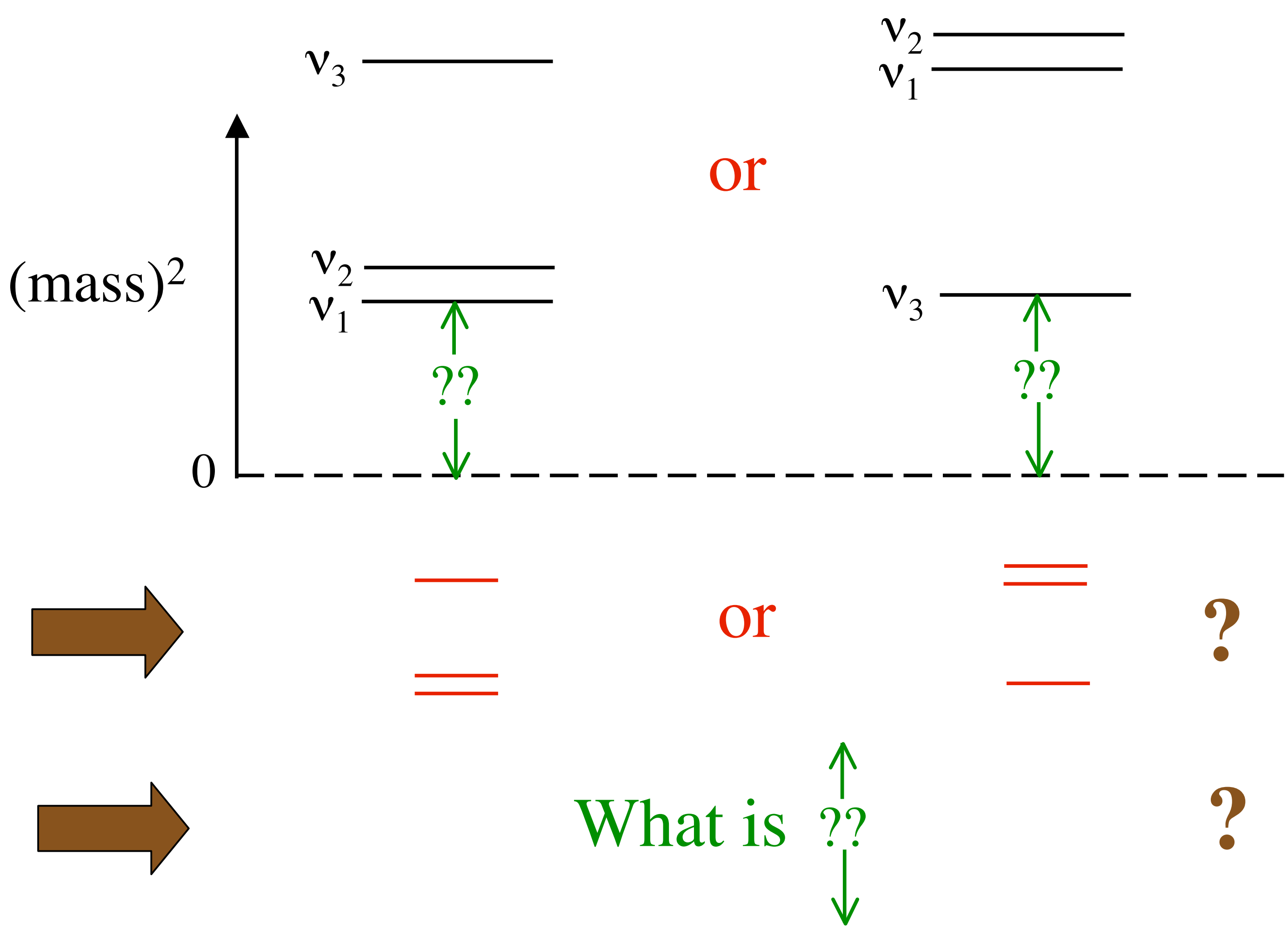
- Are there “sterile” neutrinos?
- Do neutrinos have unexpected or exotic properties?
- What can neutrinos tell us about the models of new physics beyond the Standard Model?

Neutrinos and the Cosmos

- What is the role of neutrinos in shaping the universe?
- Are neutrinos behind the matter – antimatter asymmetry of the universe?
- What can neutrinos reveal about the deep interior of the earth and sun, and about supernovae and other ultra high energy astrophysical phenomena?

Some Highlights

✦What are the masses of the neutrinos?



vs.

ν behavior in earth matter can distinguish.

The grand unified theories (GUTS) that unify the strong nuclear, electromagnetic, and weak forces favor –

GUTS relate the Leptons to the Quarks.

is un-quark-like.

The Distance from Zero

A Cosmic Connection

Cosmological Data + Cosmological Assumptions $\Rightarrow$

If there are only 3 neutrinos in the spectrum, the Mass of each of them is less than —

$$\frac{\text{Mass of an electron}}{2{,}500{,}000}\,.$$

Can cosmology turn this into a number??

✦Are neutrinos their own antiparticles?

$e^+ \neq e^-$ since Charge(e^+) = – Charge(e^-).

Similarly for the quarks.

But neutrinos have no electric charge.

Do they carry a conserved "Leptonic Charge L" that distinguishes leptons from antileptons?

$$L(\nu) = L(e^-) = +1$$

but

$$L(\bar{\nu}) = L(e^+) = -1$$

Widespread theoretical prejudice: NO.

No conserved L $\Rightarrow$ $\bar{\nu} = \nu$

To confirm there is no conserved L, seek —

Neutrinoless Double Beta Decay

Nucleus $\longrightarrow$ New Nucleus + e^- + e^-

Observation would establish that —

- Neutrinos are their own antiparticles.
- The origin of neutrino mass involves physics different from that which gives masses to electrons, quarks, protons, neutrons, humans, the earth, and galaxies.

Then neutrinos and their masses are **very** distinctive.

The Quest for the Origin of Mass

Neutrino experiments and the search for the Higgs boson both probe the origin of mass.

Theoretical arguments suggest that the physics behind neutrino mass resides at the extremely high energy where Grand Unified Theories say all the forces of nature, save gravity, become one.

✦Are neutrinos behind the matter – antimatter asymmetry of the universe?

The universe contains **MATTER**, but essentially no antimatter.

Good thing for us: Matter and antimatter annihilate each other.

This preponderance of **MATTER** over antimatter could not have developed unless the two behave differently.

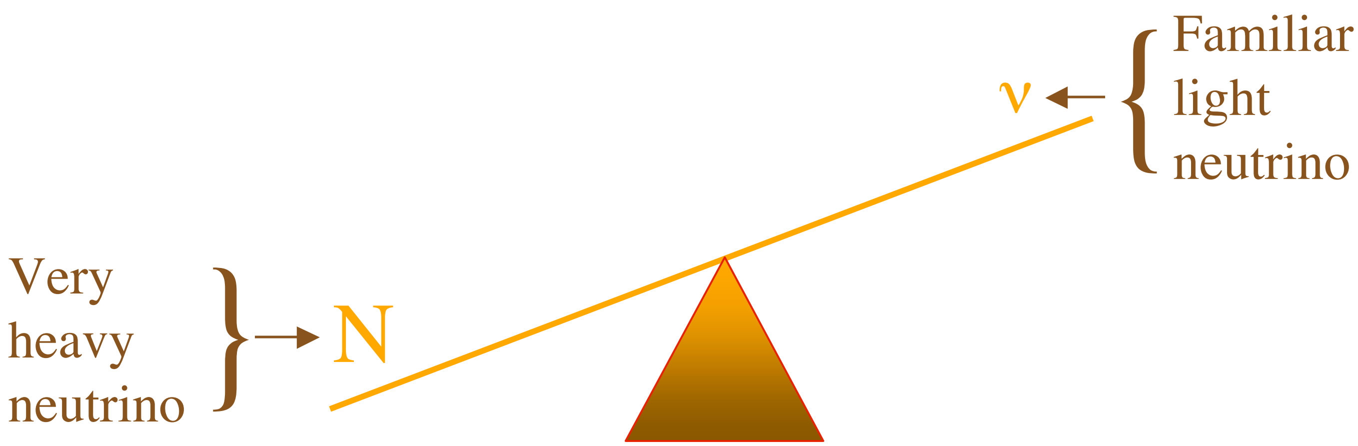
The observed difference between **QUARK** and antiquark behavior, as described by the Standard Model, is inadequate.

Could the interactions of **MATTER** and antimatter with neutrinos provide the crucial difference?

There is a natural way in which they could.

The most popular theory of why neutrinos are so light is the —

See-Saw Mechanism



The heavy neutrinos N would have been made in the hot Big Bang.

If MATTER and antimatter interact differently with these heavy neutrinos N, then we can have —

$$\text{Probability}\,[\,N \rightarrow \underbrace{e^-}_{\text{MATTER}} + \ldots\,] \neq \text{Probability}\,[\,N \rightarrow \underbrace{e^+}_{\text{antimatter}} + \ldots\,]$$

in the early universe.

This phenomenon would have led to a universe containing unequal amounts of MATTER and antimatter.

We cannot repeat the early universe.

But, if MATTER and antimatter interact differently with today's light neutrinos ν, then quite likely

$$\text{Probability}\ [\ N \rightarrow e^- + \ldots\ ] \neq \text{Probability}\ [\ N \rightarrow e^+ + \ldots\ ]$$

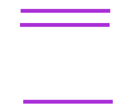
Confirm that MATTER and antimatter do interact differently with the light neutrinos.

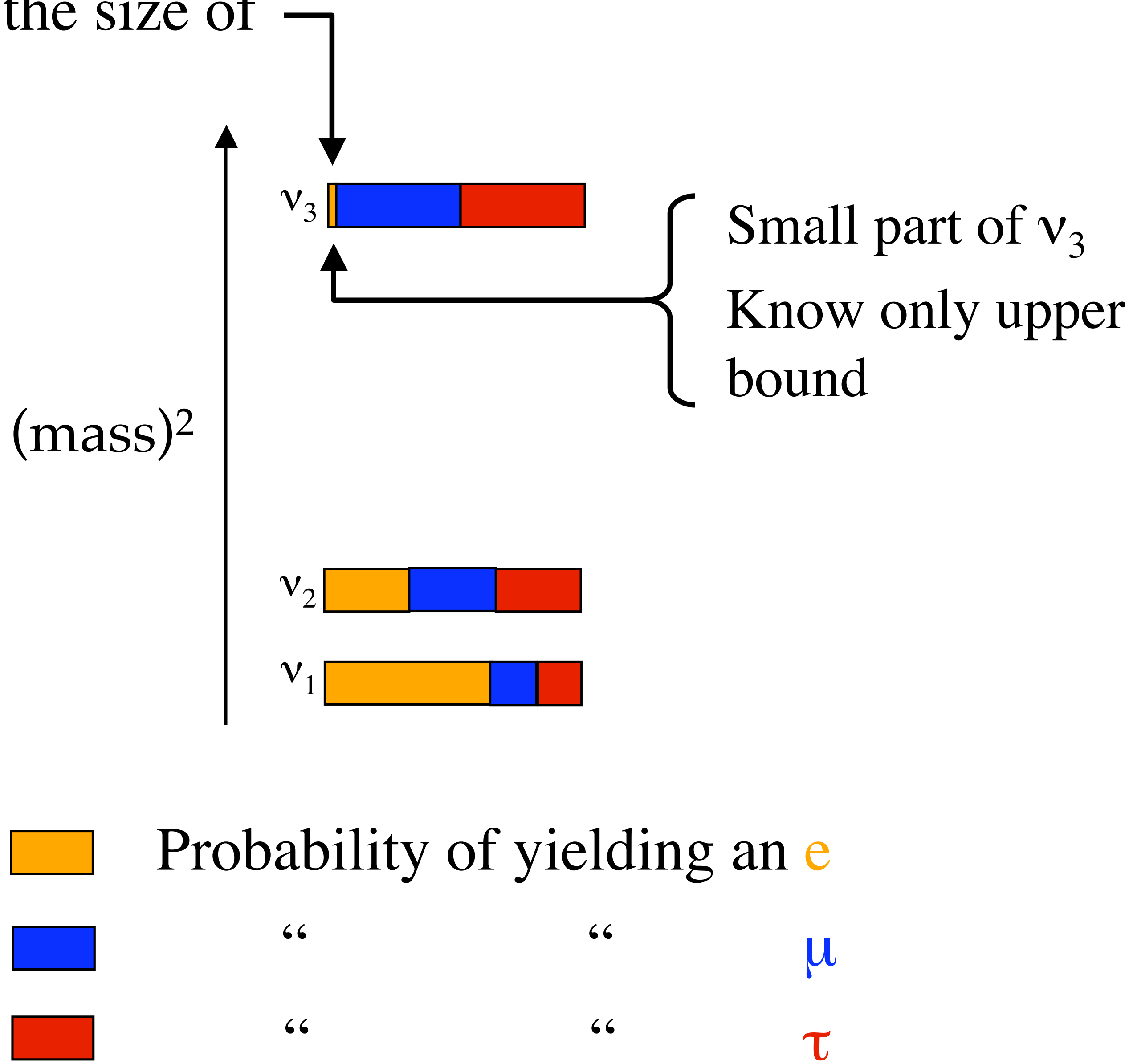
Such a difference is referred to as CP violation among neutrinos.

Principal Recommendations of the APS Multi-Divisional Neutrino Study

We recommend, as a high priority, that a phased program of increasingly sensitive searches for neutrinoless nuclear double beta decay be initiated as soon as possible.

We recommend, as a high priority, a comprehensive U.S. program to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum, and to search for CP violation among neutrinos.

The ease of finding CP violation and settling  vs.  both depend on the size of



Components of The Program

- An expeditiously deployed reactor experiment twenty times more sensitive to the small part of ν_3 than previous experiments.

- A timely accelerator experiment with comparable sensitivity to the small part of ν_3, and with sensitivity to the character of the mass spectrum.

- A proton accelerator delivering approximately ten times as many neutrinos as current ones, and an appropriately large neutrino detector giving substantial sensitivity to CP violation.

We recommend the development of a solar neutrino experiment capable of measuring the energy spectrum of neutrinos from the primary pp fusion process in the sun.

Main Report and Working Group Reports are at —

www.aps.org/neutrino.

Conclusion

We have a very rich opportunity to do exciting physics.

Neutrino physics has connections to —

Cosmology, astrophysics, nuclear physics, the origin of mass, the relation between matter and antimatter, the symmetries of nature, physics at energies where the forces of nature become unified, …

With our new-found ability to study neutrinos, they will be an important part of our quest for understanding of the physical world.